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WES 2808 for brittle fracture assessment of steel components under seismic conditions Part-IV: Change in mechanical properties and fracture toughness of steel weld HAZ by pre-strain

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Abstract

Brittle fracture of the welded steel structures during an earthquake is reported to be caused mainly by dynamic and cyclic large strain. However, effect of pre-strain to fracture toughness of the welded joint, especially heat affected zone (HAZ) was not reported enough. In this paper, effect of pre-strain in HAZ tensile properties and critical CTOD was studied by using the simulated HAZ specimens of 490MPa class steel. Change in tensile properties of simulated HAZ by pre-strain was as well as that of base metal. The amount of change in strength of simulated HAZ was possible to describe by the same numerical formula as the base metal. In addition, the amount of temperature shift at critical CTOD of 0.1mm of simulated HAZ by the pre-strain was as well as that of base metal which has the same amount of the change in flow stress by the pre-strain.

Keywords: fracture toughness; mechanical properties; pre-strain; HAZ

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1. Introduction

Brittle fracture of the welded steel structures during an earthquake is reported to be caused mainly by dynamic and cyclic large strain. However, effect of pre-strain to the fracture toughness of the welded joint, especially heat affected zone (HAZ) was not reported enough.

The CTOD toughness is very important to a fracture assessment procedure, WES2808. However, in those cases where the CTOD fracture toughness data are not available, the CTOD toughness may be estimated from the Charpy impact energy. WES2805 presents the correlation between the CTOD fracture toughness, δ_{cr} [mm], and the Charpy energy, vE [J] which is applicable to structural steels with tensile strengths of 400MPa to 780MPa. However, the applicability to the HAZ of this correlation is unclear.

In this paper, effect of pre-strain in HAZ tensile properties, Charpy impact properties and critical CTOD was studied by using the simulated HAZ specimens of 490MPa class steel. In addition, using these results, the applicability to the HAZ of the correlation presented by WES2805 was investigated

2. Experimental Procedure

2.1. Material

The simulated HAZ specimens were prepared from the 490MPa class steel. The chemical compositions and mechanical properties of the steel are shown in Table 1 and 2. Thermal cycle condition is shown in Table 3. This condition simulates CGHAZ of the weld joint produced by SAW of 2.6kJ/mm using a steel plate with a thickness of 15mm. The test specimen of thermal cycle is shown in Fig. 1. The thermal cycle zone is 10 mm × 45 mm, the temperature was controlled by attaching a thermocouple at its center.

Table 1 Chemical compositions of 490MPa class steel

C	Si	Mn	P	S	Nb	Ceq
0.16	0.25	1.53	0.016	0.002	0.01	0.43

Ceq=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14

Table 2 Mechanical properties of 490MPa class steel

σ_Y(MPa)	σ_T(MPa)	R_Y(%)=σ_Y/σ_T	ε_f(%)	vE_0(J)
365	536	68	37	118

Table 3 Thermal cycle condition simulating the HAZ

Peak temperature (℃)	Cooling time from 800℃ to 500℃ (sec.)
1350	20

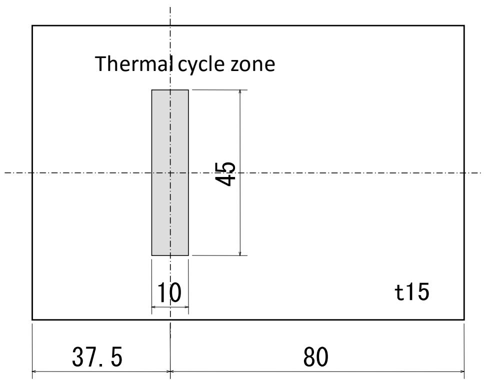


Fig.1 Shape of the simulated HAZ specimen

2.2. Method of applied pre-strain

The test specimen of applied pre-strain is shown in Fig. 2. Since uniform elongation of this material was about 10%, pre-strain of 8% was applied.

2.3. Tensile test

Tensile test specimen is shown in Fig.3. The sampling positions of tensile test specimens are shown in Fig.4 and Fig.5. The parallel portion of tensile test specimens was taken to be the thermal cycle material, and the thermal cycle and pre-strain material, respectively. And all test specimens were taken to the center of the thickness of the plate.

Tensile test was performed at room temperature.

2.4. CTOD and Charpy impact test

The CTOD test specimen, three-point bending test specimen, is shown in Fig. 6. The ratio of crack length over test specimen width was 0.5. The sampling position of CTOD test specimen is shown in Fig.7 and Fig.8. The mechanical notch tip and ligament portion were set to the thermal cycle material, and the thermal cycle and pre-strain material, respectively.

The Charpy impact test specimens, V-notch test specimens of JIS Z-2242, were prepared by thermal cycle material, and the thermal cycle and pre-strain material. The sampling position of Charpy impact test specimen is shown in Fig.4 and Fig.9.

And the CTOD and charpy impact test specimens were taken to the center of the thickness of the plate.

The specific test temperature is shown in table 4. These temperatures was decided at which it is approximately δcr = 0.1mm and vE=25 J.

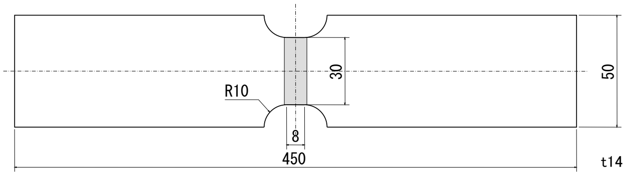


Fig.2 Test specimen to apply pre-strain.

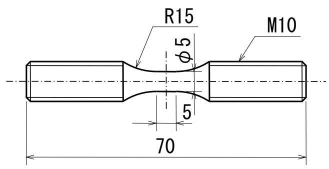


Fig.3 Tensile test specimen.

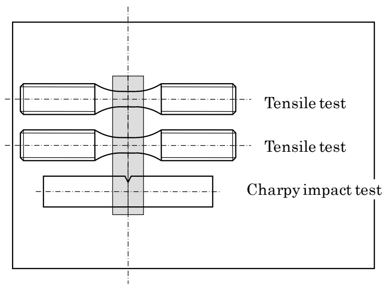


Fig.4 Position of tensile test specimen and charpy impact test specimen in thermal cycle material

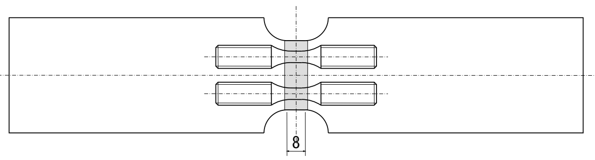


Fig.5 Position of tensile test specimen in thermal cycle and pre-strain material

Table 4 Test temperature of CTOD and Charpy impact test

Pre-strain(%)	CTOD test temperature(℃)	Charpy impact test temperature(℃)
0	-40, -20, 0	-40, -20, 0, 20, 40
8	0, 20, 30, 40	0, 20, 30, 40

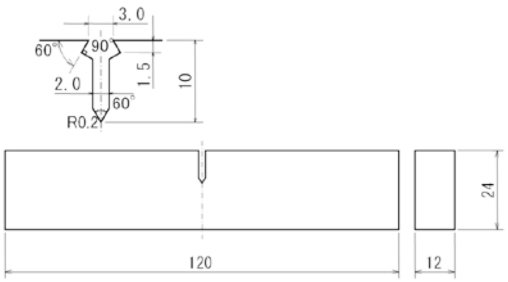


Fig. 6 CTOD test specimen

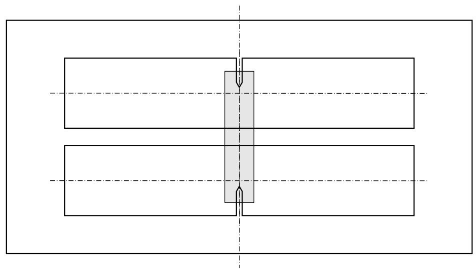


Fig. 7 Position of CTOD test specimen in thermal cycle material.

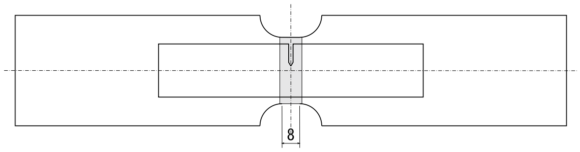


Fig. 8 Position of CTOD test specimen in thermal cycle and pre-strain material.

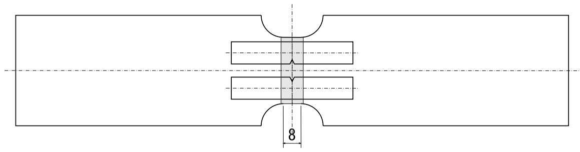


Fig. 9 Position of Charpy test specimen in thermal cycle and pre-strain material.

3. Result

3.1. Change in tensile properties of thermal cycle material by pre-strain

The tensile test result of thermal cycle and pre-strain material is shown in table 5. When the pre-strain is 8%, the yield strength is increased about 190MPa and the tensile strength is increased about 60MPa.

The change in true stress – true strain curve by pre-strain of thermal cycle material is shown in Fig. 10. Actually measured given pre-strain amount is certainly 8%.

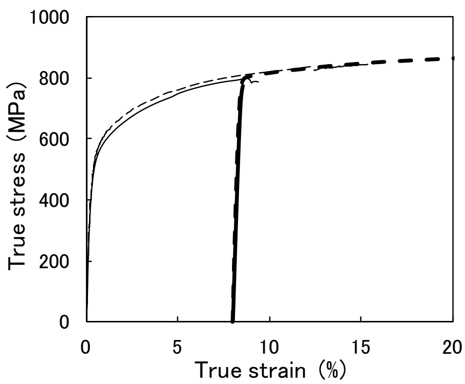


Fig. 10 Change in true stress-true strain curve of thermal cycle material by pre-strain.

Table 5 Tensile test result of thermal cycle and pre-strain material

Pre-strain(%)	σ_Y(MPa)	σ_T(MPa)	R_Y(%)=σ_Y/σ_T	ε_T(%)	ε_f(%)
0	502	744	67	10.2	61
	490	730	67	9.2	64
8	786	800	98	2.4	54
	781	796	98	2.5	54

3.2. Change in critical CTOD of thermal cycle material by pre-strain

The CTOD test result in thermal cycle and pre-strain material is shown in Fig. 11. The temperature shift, ΔT_{PD}, was defined as the difference of the temperature at critical CTOD of 0.1mm, $T_{\delta\ cr\ =\ 0.1mm}$. The $T_{\delta\ cr\ =\ 0.1mm}$ of the thermal cycle material is -24°C, and that of the pre-strain material is 38°C. Therefore, the ΔT_{PD} is 62 °C.

3.3. Change in Charpy impact properties of thermal cycle material by pre-strain

The Charpy impact test result of the thermal cycle material is shown in Fig. 12. The temperature $T_{vE=25J}$ of the thermal cycle material is 4°C, and that of the pre-strain material is 25°C.

4. Discussion

4.1. Effect of pre-strain in HAZ tensile properties

Empirical formulae are given by Shimada et al. (2016) for estimating the static yield strength $\sigma_{Y0}{}^{pre}(T_0)$ and tensile strength $\sigma_{T0}{}^{pre}(T_0)$ at the room temperature T_0 with pre-strain ε_{pre}:

$$\sigma_{Y0}{}^{pre}\left(T_0\right)=\sigma_{Y0}\left(T_0\right)+34\left(\frac{E}{\sigma_{Y0}\left(T_0\right)}\right)^{1/4}\cdot\ln\left(1+34\varepsilon_{pre}\right) \tag{1}$$

$$\sigma_{T0}{}^{pre}\left(T_0\right)=\sigma_{T0}\left(T_0\right)+750\varepsilon_{pre} \tag{2}$$

The applicability of Eq. (1) and (2) is investigated in the simulated HAZ. The result is shown in Fig.13. Fig.13 includes the data of APD committee. Estimated yield and tensile strength are good agreement with measured ones. This indicates that the strength change in the simulated HAZ by pre-strain is governed by the stress-strain curves as well as the base metal.

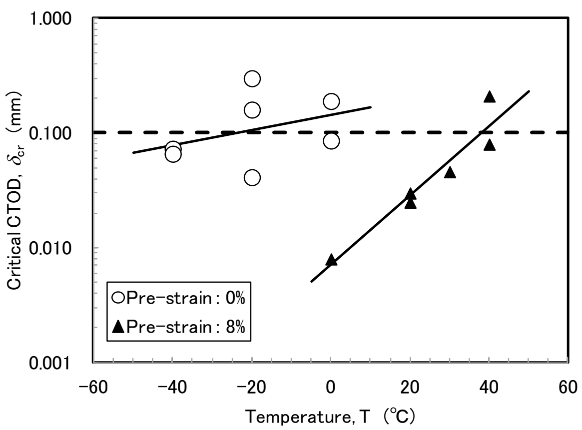


Fig. 11 CTOD test result of thermal cycle and pre-strain material

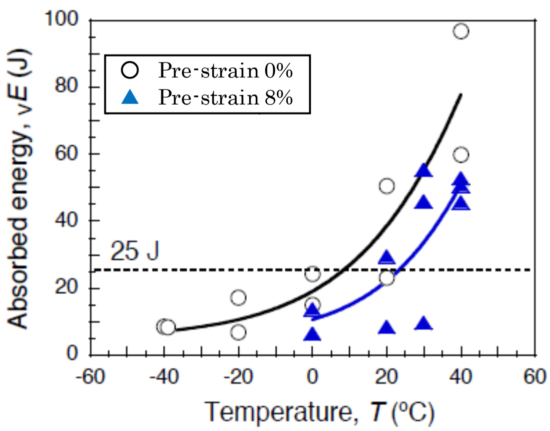


Fig. 12 Charpy impact test Result of thermal cycle and pre-strain material

4.2. Effect of pre-strain in temperature shift of critical CTOD at simulated HAZ

When structural steel is subjected to pre-strain and dynamic load, typically fracture toughness is lowered, ductile - brittle transition temperature are known to migrate to the high temperature side. From engineering handling in WES2808, it was to evaluate the fracture toughness of the flow stress elevation,$\Delta\ \sigma_f^{PD}$ as an indicator.

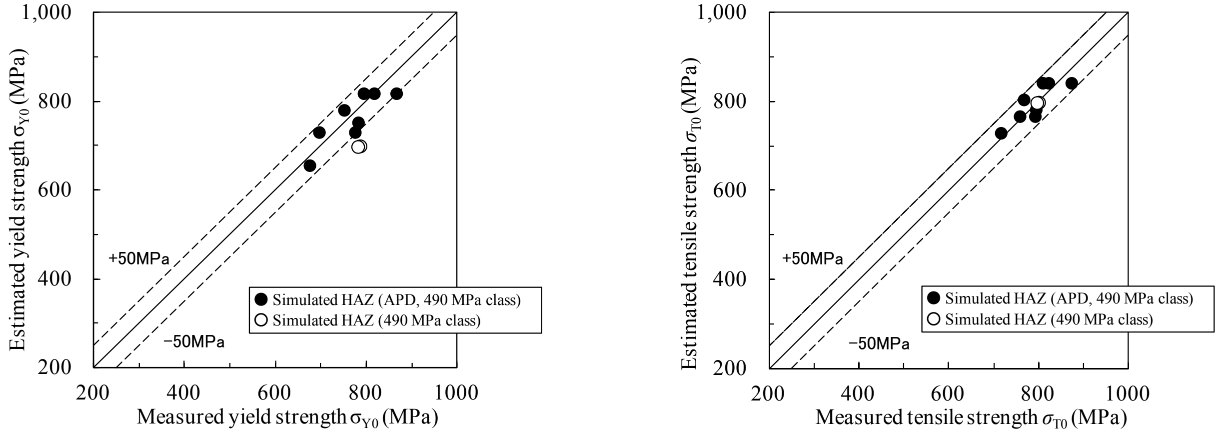
$\Delta\sigma_f^{PD}$ at simulated HAZ was calculated by the following equation:

$$\Delta\sigma_f^{PD} = (\Delta\sigma_Y + \Delta\sigma_T)/2 \tag{3}$$

where ΔT_{PD} at CTOD toughness levels of 0.05mm to 0.1mm was focused and $\Delta\sigma_Y$ and $\Delta\sigma_T$ are the increase in the yield strength and tat in the tensile strength, respectively.

In WES2808, although the temperature shift, ΔT_{PD} is constantly 40 ℃ at 100 $\leqslant \Delta\sigma_f^{PD} \leq$ 300MPa as a target the base material, it is about 60 ℃ in thermal cycle material as shown in Fig. 14. The tensile strength of simulated HAZ is about 700MPa, therefore they were compared with $\Delta\sigma_f^{PD}$ -ΔT_{PD} in the base material of the 590MPa class. By the comparison with the equivalent strength class, ΔT_{PD} of simulated HAZ can be considered to be equivalent to the base material.

However there are not enough numbers of data about the strength and toughness changes by pre-strain for the HAZ, further investigations will be necessary.



(a) Yield strength

(b) Tensile strength

Fig. 13 Estimation of change in strength of simulated HAZ by pre-strain

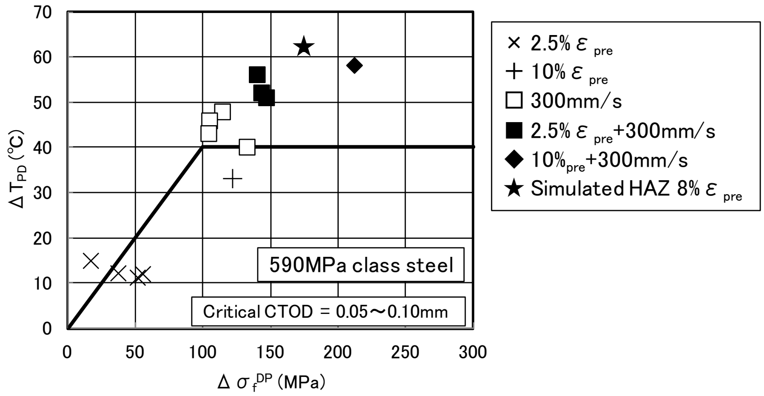


Fig.14 Relationship between temperature shift and flow stress change.

5. The applicability to the HAZ of the correlation presented by WES2805

In assessments by WES2808, it is desirable to use the critical CTOD of the steel obtained by experiment. However, the toughness of most structural steels is generally evaluated by Charpy energy. Therefore, it is necessary to determine the correlation of Charpy energy and the critical CTOD.

WES2805 presents the correlation between the CTOD fracture toughness, δ_{cr} [mm], and the Charpy energy, *vE* [J] which is applicable to structural steels with tensile strengths of 400MPa to 780MPa, in the form:

$$\delta_{cr}(T) = \frac{1}{250}\mathrm{v}E(T+\Delta T), \Delta T = 87 - 0.10\sigma_{Y0}(T_0) - 6\sqrt{t} \tag{4}$$

where $\mathrm{v}E(T+\Delta T)$ is the Charpy energy [J] at the temperature of $T+\Delta T$, $\sigma_{Y0}(T_0)$ is the yield strength [MPa] at the room temperature T_0 and t is the plate thickness [mm] (= thickness of CTOD toughness specimen).

This correlation is in consideration of the transition temperature difference between the dynamic Charpy test and static CTOD test. Furthermore, it is taken into account the thickness effect of CTOD test. By systematic experiments performed by FTC Committee, it is revealed that represented in the form of $6\sqrt{t}$.

In order to confirm the applicability to the HAZ of this correlation, the data shown in table 6 is used. For each steel, the difference ΔT between the temperatures at vE=25J and δcr=0.1mm is calculated, and the relationship between yield strength σ_{Y0} and $\Delta T + 6\sqrt{t}$ is evaluated.

The correlation in simulated HAZ is equivalent to the base material obtained in WES2805, so correlation equation of WES2805 is considered to be applied in the welding heat affected zone.

Table 6 Numerical approximation results of Charpy transition curve and critical CTOD transition curve in thermal cycle material

Steel	Thickness (mm)	Yield strength $\sigma_{Y0}(T_0)$ (MPa)	CTOD specimen thickness t (mm)	vT_E (°C)	$T_{vE=25J}$ (°C)	vE_{shelf} (J)	k_a	T_δ (°C)	$T_{\delta=0.1mm}$ (°C)	δ_{shelf} (mm)	k_b	Reference
490MPa class	15	496	12	(76)	4	(266)	-0.031		-24			This study
590MPa class	32	450	32	51	8	203	-0.043	-2	-22	0.47	-0.068	Kanazawa et al. (1978)
780MPa class	30	579	30	40	3	191	-0.041	29	9	0.35	-0.047	

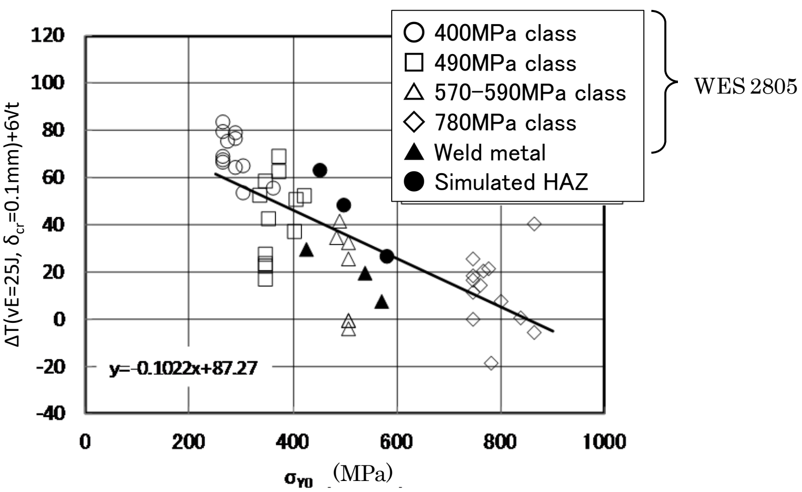


Fig.15 Relationship between yield strength and ΔT

6. Conclusion

Change in mechanical properties and fracture toughness of steel weld HAZ by pre-strain was investigated. As a result, the follow conclusions can be made.

1) The change in mechanical properties of the simulated HAZ having 490MPa class strength is equivalent to base metal having tensile properties equal to simulated HAZ.
2) The change in fracture toughness of the simulated HAZ having 490MPa class strength is equivalent to base metal having 590MPa class strength.
3) The correlation between the CTOD fracture toughness and the Charpy energy in simulated HAZ is equivalent to the base material obtained in WES2805.

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